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[54] **FLUE GAS RECIRCULATION SYSTEM AND METHOD**

[75] Inventors: **Eric L. Berger**, Bakersfield, Calif.; **Karl W. Kolthoff**, Shaw Centre, Singapore; **Thomas J. Rankin**, Bakersfield, Calif.

[73] Assignee: **Texaco Inc.**, White Plains, N.Y.

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[51] **Int. Cl.**[7] **F23C 9/00**

[52] **U.S. Cl.** **431/9**; 431/4; 431/5; 431/12; 431/115

[58] **Field of Search** 431/4, 5, 9, 115, 431/116, 12; 110/205, 206, 207, 188, 190, 234

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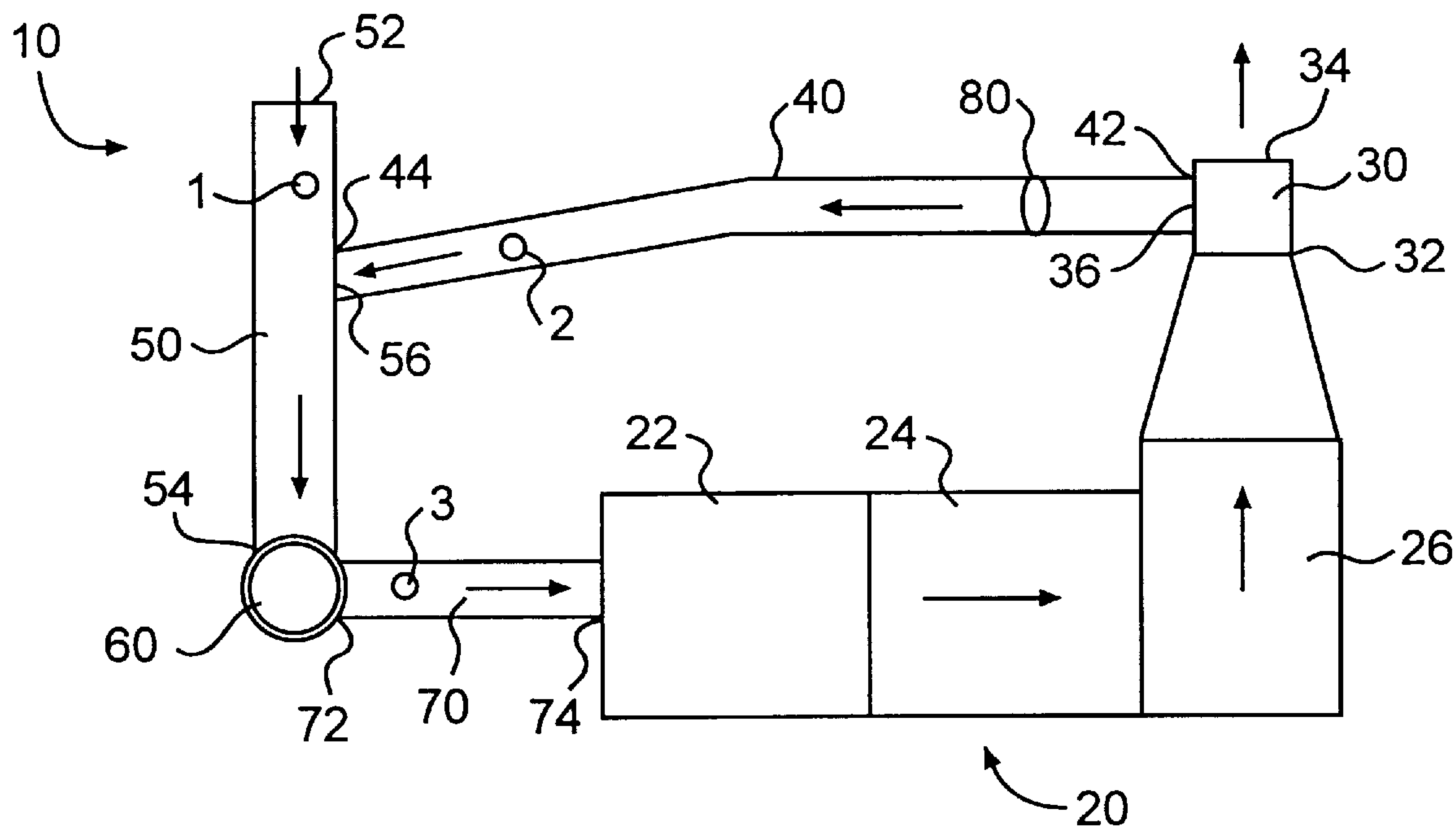
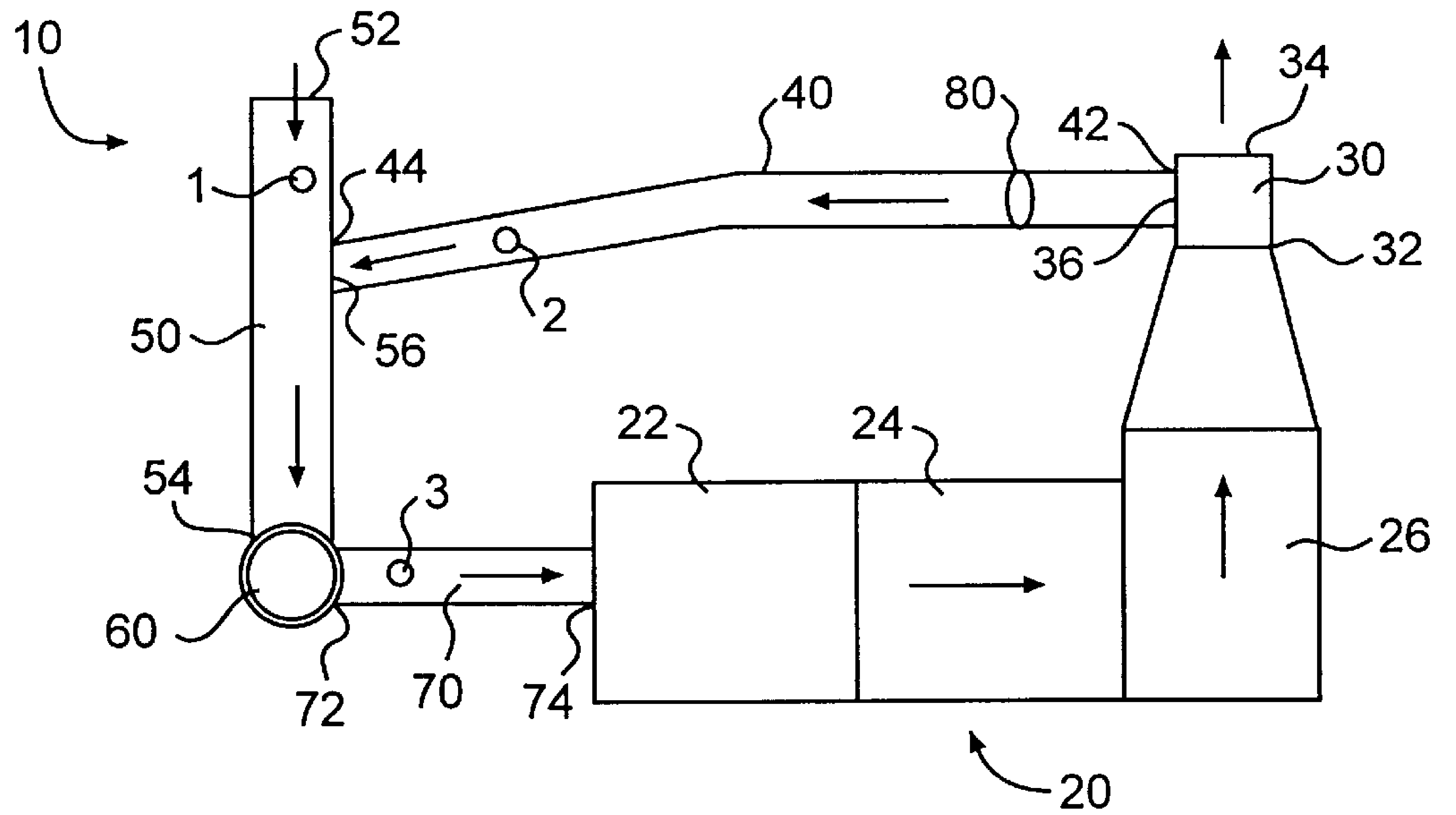
Primary Examiner—Carl D. Price
Attorney, Agent, or Firm—Harold J. Delhommer; Howrey & Simon

[57] **ABSTRACT**

The present invention relates to an apparatus and method for improving the economics of flue gas recirculation. In particular, the present invention relates to an apparatus for the minimization of oxides of nitrogen ("NO_x") in the exhaust gas of various combustion processes via balanced pressure drops of the recirculation gas, and a method for the calculation of flue gas recirculation percentage. The flue gas recirculation system achieves the balanced pressure drops by sizing the air intake line and recirculation line associated with the system.

10 Claims, 3 Drawing Sheets




10
52
40
80
42
34
30
1
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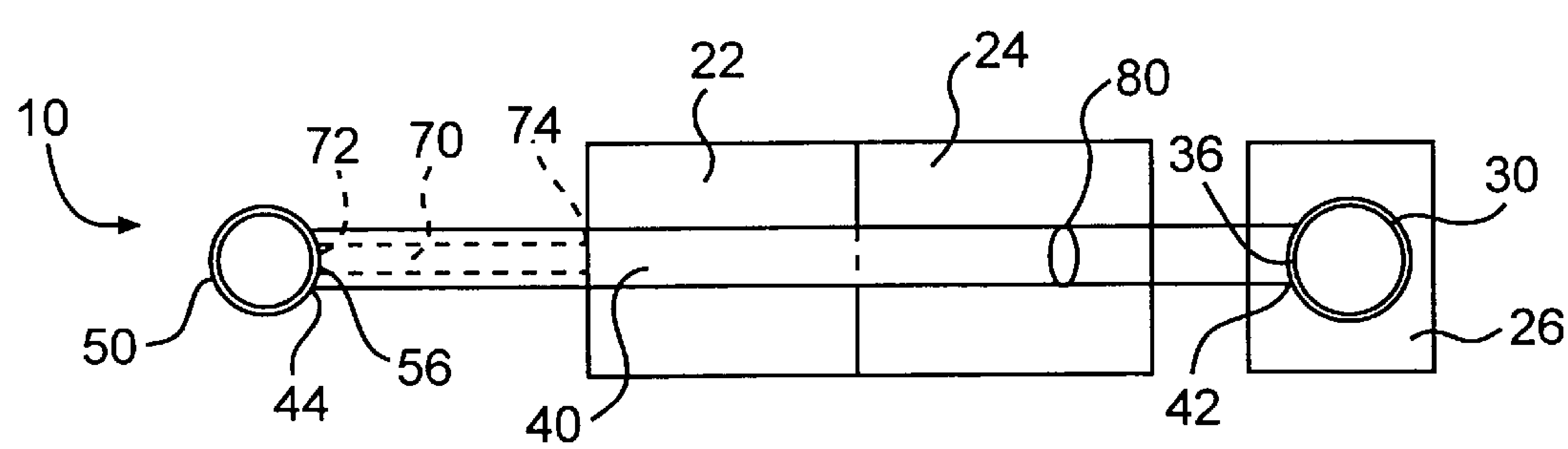
36
32
2
50
56
22
24
54
3
26
60
72
70
74
20

FIG. 1


22
24
80
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72
70
74
36
30
50
44
56
40
42
26

FIG. 2

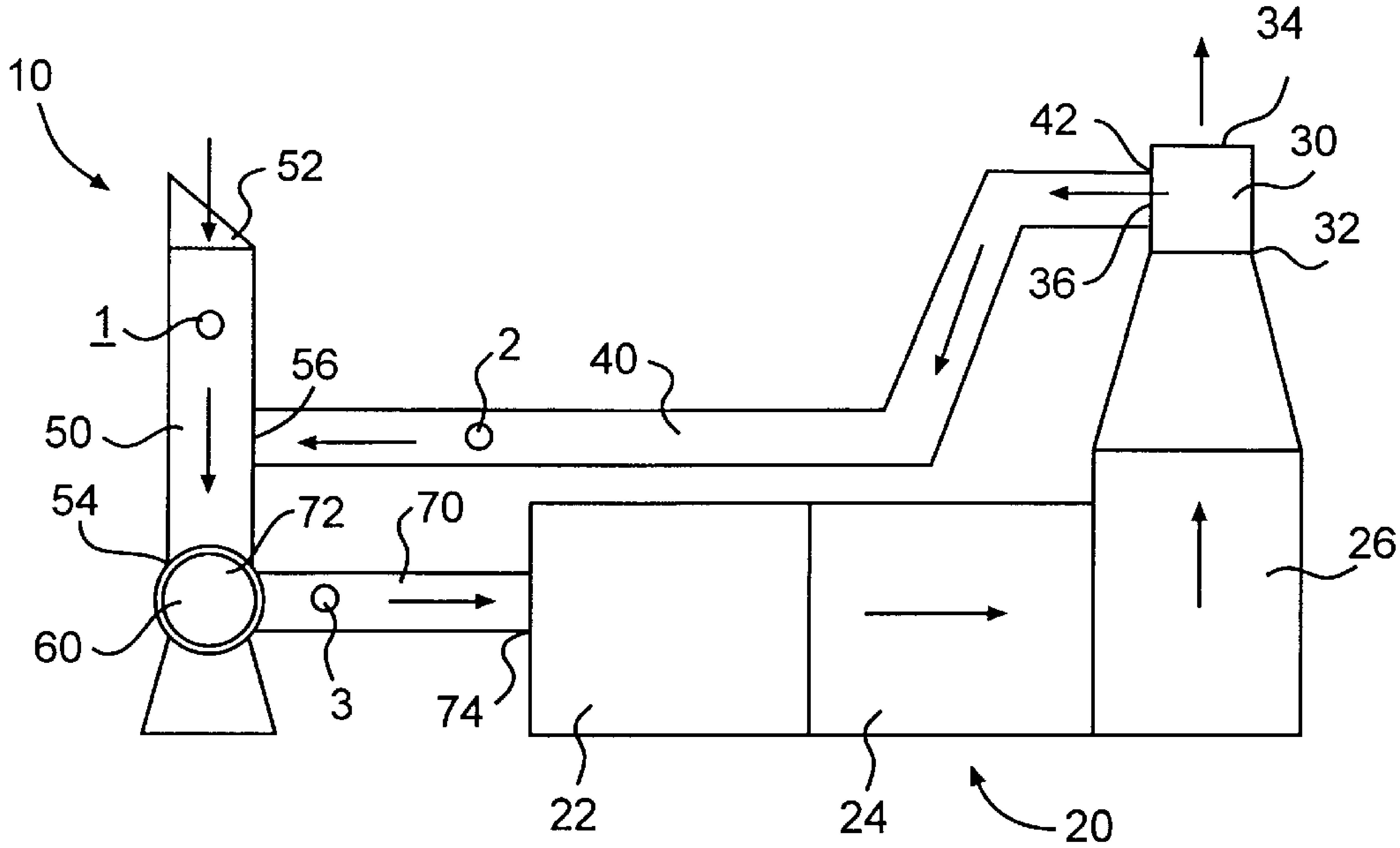
10
52
1
50
56
2
40
42
34
30
36
32
54
72
70
60
3
74
26
22
24
20

FIG. 3

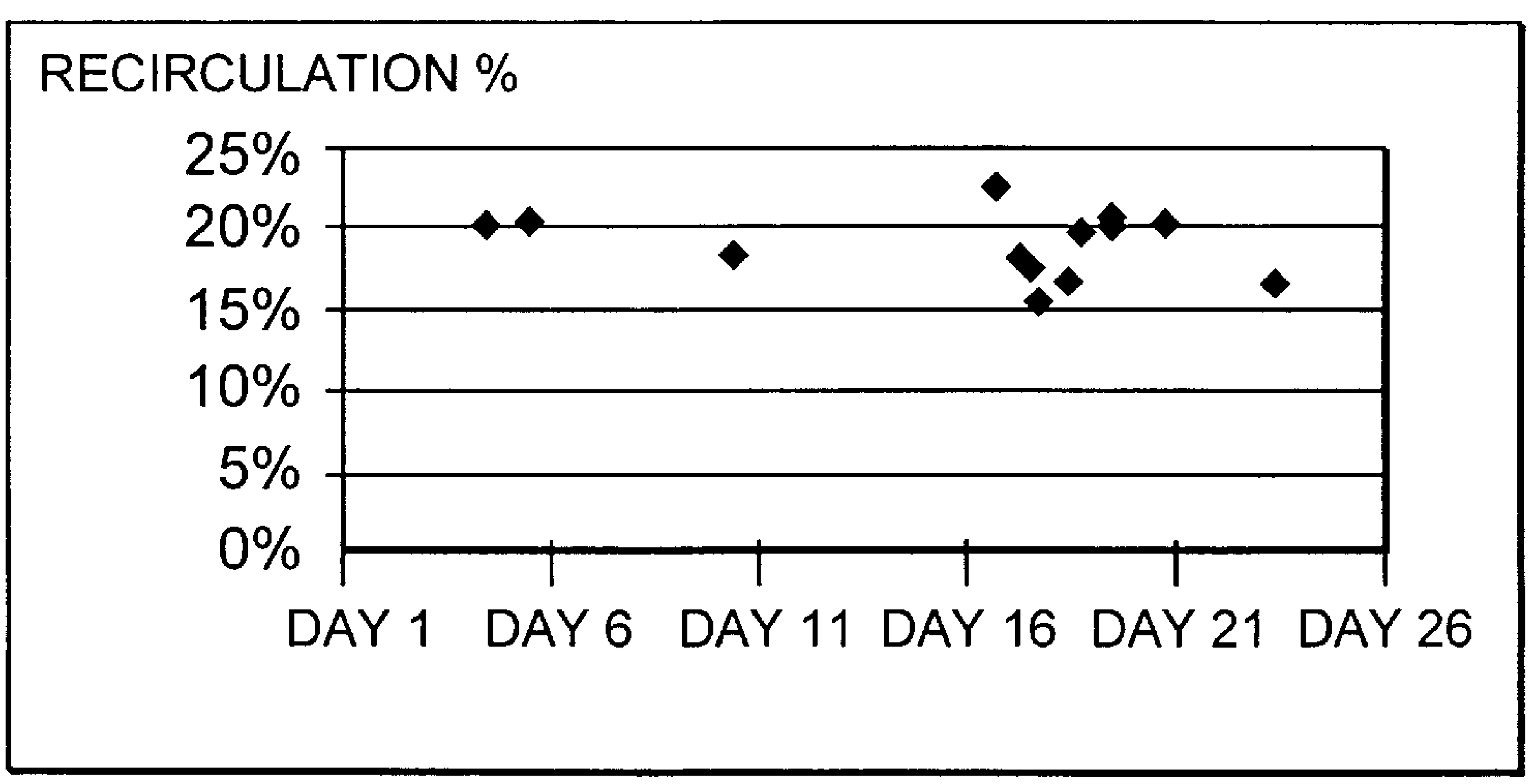
RECIRCULATION %
25%
20%
15%
10%
5%
0%
DAY 1
DAY 6
DAY 11
DAY 16
DAY 21
DAY 26

FIG. 4

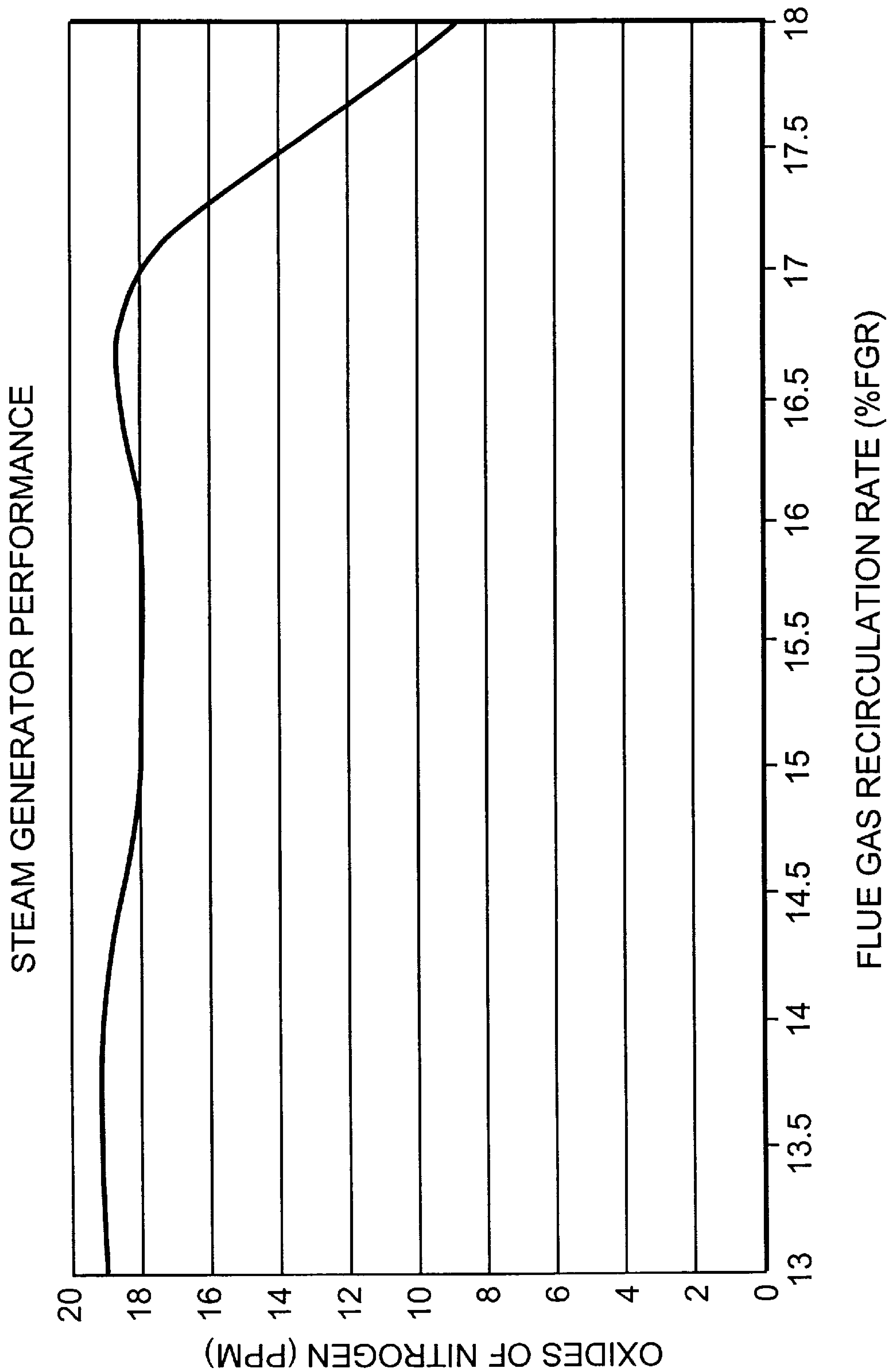
STEAM GENERATOR PERFORMANCE
OXIDES OF NITROGEN (PPM)
0
2
4
6
8
10
12
14
16
18
20
13
13.5
14
14.5
15
15.5
16
16.5
17
17.5
18
FLUE GAS RECIRCULATION RATE (%FGR)

FIG. 5

FLUE GAS RECIRCULATION SYSTEM AND METHOD

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to an apparatus and method for improving the economics of flue gas recirculation. In particular, the present invention relates to an apparatus and method for the minimization of oxides of nitrogen ("NO_x") in the exhaust gas of various combustion processes.

2. Related Art

The minimization of oxides of nitrogen ("NO_x") in the exhaust gas of various combustion processes has been mandated by pollution control agencies throughout the country. Oilfield steam generators represent one of many industrial combustion processes where implementation of NO_x control has become widespread. One of the ways in which NO_x control is accomplished is to recirculate a percentage of the flue gas, or exhaust gas, (often 10%–20%) to mix with the inlet air.

The conventional NO_x control systems, which utilize Flue Gas Recirculation ("FGR"), are extremely costly to manufacture, operate, and maintain due to the elaborate control systems that are required for effective performance of the system. Additionally, such systems, while substantially increasing generator operating cost, typically reduce the effective generator capacity.

One method of controlling the flue gas recirculation percentage is to provide control valves within the system to adjust the mixture of ambient air and flue gas to obtain a desired percentage. In the system disclosed in U.S. Pat. No. 5,040,470, the percentage of recirculated flue gas in the air inlet stream must be controlled to a reasonable precision. If this percentage is too high, generator output is reduced. If the percentage is too low, NO_x reduction is insufficient. In this system, a control valve in the recirculation line is used to control the amount of flue gas recirculation. This valve works in tandem with the main air inlet valve, which controls the ambient air inlet rate. The main air inlet valve disclosed in U.S. Pat. No. 5,040,070 is itself a replacement for adjustable dampers, which are typically located between the blower and the burner section on units without NO_x control. Under typical operating conditions, the main air inlet valve will be a source of significant frictional pressure drop, which must be overcome with additional energy consumption at the blower. To monitor the recirculation percentage, oxygen sensors are utilized. These sensors are used to monitor the percentage of flue gas recirculation, providing feedback to a recirculation rate control valve. The oxygen sensors add significantly to the expense of the system.

Conventional systems use active control in order to reach and maintain a selected recirculation percentage. Active control involves constant adjustment of control valves, and heat exchangers in order to operate the system at the selected recirculation percentage. Operators manually change valve settings or damper positions. In other systems, sensors integrated with control systems cause the system to alter relative valve positions and thermal conditions of the system in order to maintain the selected recirculation percentage. This active control adds significantly to the installation and operational costs of NO_x control systems.

Other patents disclose controlling flue gas recirculation through an elaborate array of specialized burners, fans and dampers that alter the temperature of the flue gas in order to reduce noxious emissions. Such a system is disclosed in U.S. Pat. No. 4,659,305. This system uses conventional dampers and air diffusers, in conjunction with a recirculation fan, to enable the flue gas to be recirculated.

It is also desirable to calculate the flue gas recirculation percentage for monitoring purposes. Several conventional methods exist to calculate the percentage of flue gas recirculation (FGR). For example, oxygen sensors have been used to monitor the amount of oxygen in the combustion air. The percentage of FGR is then calculated from the oxygen sensor readings. However, the oxygen sensors are costly to install and maintain. Monitoring the flue gas recirculation percentage has also been achieved by metering the flow rate of the flue gas returned, or by performing a material balance using the temperature at different points in the system. However, the equations utilized to perform these calculations typically amount to a rough approximation of the actual flue gas recirculation percentage. The equations are generally inaccurate because they do not account for the heat added to the system by the mechanical inefficiencies in the blower.

Thus, there is a need in the art for a simple and inexpensive system for controlling flue gas recirculation percentage to minimize NO_x emissions. Particularly, there is a need in the art for a system that eliminates the need for active control to maintain a selected flue gas recirculation percentage. There is a further need in the art for an improved method for calculating flue gas recirculation (FGR) percentage for monitoring purposes.

SUMMARY OF THE INVENTION

The present invention solves the problems with, and overcomes the disadvantages of conventional systems for flue gas recirculation and conventional methods of calculating the flue gas recirculation percentage.

The present invention relates to an apparatus and method for improving the economics of flue gas recirculation. In particular, the present invention relates to an apparatus and method for the minimization of oxides of nitrogen ("NO_x") in the exhaust gas of various combustion processes via maintaining balanced pressure drops of the recirculation gas.

In one aspect of the present invention, a flue gas recirculation system is provided. The system is used with a combustion generator for providing a selected percentage of flue gas recirculation. The system includes an exhaust stack for exhausting flue gas from the combustion generator. The exhaust stack has a stack inlet which is coupled to the combustion generator, a stack outlet which exhausts flue gas to the atmosphere, and a take off point. The take off point is a point along the exhaust stack between the stack inlet and the stack outlet. The system further includes a recirculation line that has a recirculation inlet which is coupled to the take off point, and a recirculation outlet. There is an air inlet line for providing air to the combustion generator. The air inlet line has an air inlet which is open to the atmosphere, and an air outlet which is coupled to the combustion generator. The recirculation outlet is coupled to the air inlet line at a combination point. The combination point is a point along the air inlet line between the air inlet and the air outlet. The air inlet line is sized relative to the size of the recirculation line such that the air inlet pressure drop plus the exhaust stack pressure drop equals the recirculation line pressure drop, thereby providing the selected percentage of flue gas recirculation.

The recirculation system may further be provided with a line having an inlet and an outlet. The outlet is coupled to the combustion generator and the inlet is coupled to a blower. The blower may have a variable speed drive.

In order to monitor the flue gas recirculation percentage, in another aspect of the invention, temperature sensors are provided in the recirculation system. The first temperature sensor is placed in the air inlet line. The second temperature sensor is placed in the recirculation line. The third temperature sensor is placed in the line connecting the blower and the combustion generator burner section. The temperatures are measured, and the flue gas recirculation percentage is calculated according to an equation which accounts for heat added to the system due to mechanical inefficiencies in the blower.

The flue gas recirculation percentage is calculated by using the temperature sensors described above. Three temperatures are measured: first temperature (T_1) at the first temperature sensor; a second temperature (T_2) at the second temperature sensor; and a third temperature (T_3) at the third temperature sensor. A temperature factor (T_3') is then calculated by subtracting the temperature of the blower from T_3. Finally, the flue gas recirculation percentage is calculated using the following equation:

$$FGR = \frac{(1.015 * T_3' - T_1)}{(1.087 * T_2 - 1.015 * T_3')}$$

Accordingly, the present invention provides a system for flue gas recirculation wherein the recirculation is achieved by balanced pressure drops without active control of the system. The present invention further provides a method for calculating the flue gas recirculation percentage which takes into account the ambient effects of the system and the surrounding environment.

Features and Advantages

The invention provides a simple apparatus for flue gas recirculation and a method of calculating the flue gas recirculation percentage. The system is configured such that no active control is required to perform the flue gas recirculation. The system of the present application can typically be installed for 10% of the cost of existing systems. The system and method of the present invention simplifies operational control and compliance monitoring as compared with conventional systems.

Because the present system does not require an air inlet control valve, it is possible to utilize the balanced pressure drop approach to achieve simple, reliable control of the recirculation percentage. Considerable savings are obtained from not having to purchase and control an air inlet control valve.

The present invention can utilize a variable-speed drive for the blower to control the air inlet rate. The variable speed drive minimizes energy consumption.

Furthermore, the temperature sensors used in the system and method of the present invention are less costly and easier to use than the oxygen sensors of the conventional systems.

A simple pressure drop device, such an orifice plate or a manually operated butterfly valve, could be installed in the recirculation line to provide some adjustability to the system. However, once the desired recirculation percentage is obtained, on-line adjustment is not necessary.

Additional features and advantages of the invention will be set forth in the description that follows, and in part will be apparent from the description, or may be learned in practice of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the features, advantages, and principles of the invention.

FIG. **1** is a side-elevation view of one embodiment of the system of the present invention.

FIG. **2** is a plan view of the system shown in FIG. **1**.

FIG. **3** is a side-elevation view of another embodiment of the system of the present invention.

FIG. **4** is a graph of results (Recirculation % as a function of time) using the system shown in FIG. **3**.

FIG. **5** is a graph of steam generator performance (oxides of nitrogen in parts per million (ppm) as a function of Flue Gas Recirculation (FGR %))using the system of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. The exemplary embodiment of this invention is shown in some detail, although it will be apparent to those skilled in the relevant art that some features which are not relevant to the invention may not be shown for the sake of clarity.

Referring first to FIGS. **1** and **2**, there is illustrated an exemplary embodiment of the present invention. The arrows displayed in the figures are indicative of the airflow and gas flow direction.

A typical combustion generator **20** is coupled to a flue gas recirculation system shown generally by reference numeral **10**. A recirculation line **40** provides communication between an exhaust stack **30** of the combustion generator **20** and an air inlet line **50** of the recirculation system **10**. As would be readily apparent to one of skill in the relevant art, the combustion generator **20** comprises a burner section **22**, a generator section **24**, a convection section **26**, and exhaust stack **30**.

The air inlet line **50** has an air inlet **52**, which is open to the atmosphere, and an air outlet **54** which feeds into the combustion generator **20**.

The exhaust stack **30** has a stack inlet **32**, a stack outlet **34** and a take off point **36**. The stack inlet **32** is coupled to the combustion generator **20** and the stack outlet **34** is open to the atmosphere. The take off point **36** is disposed between the stack inlet **32** and the stack outlet **34**.

The recirculation line **40** has a recirculation inlet **42** and a recirculation outlet **44**. The recirculation inlet **42** is coupled to the take off point **36** and the recirculation outlet **44** is coupled to the air inlet line **50** at a point **56** between the air inlet **52** and the air outlet **54**, also known as the combination point **56**. The recirculation system **10** may also include a hose, or other type of line, **70** having a hose inlet **72** and a hose outlet **74**. The hose outlet **74** is connected to the combustion generator **20** at the burner section **22**. The hose inlet **72** is connected to a blower **60** disposed between the hose **70** and the air inlet line **50**. The blower **60** is coupled to the air outlet **54** and the hose inlet **72**. Blower **60** is preferably a variable speed drive blower.

In order to monitor the flue gas recirculation percentage, temperature sensors **1**, **2**, **3** are provided in the recirculation system **10**. The first temperature sensor **1** is placed in the air inlet line **50**. The second temperature sensor **2** is placed in the recirculation line **40**. The third temperature sensor **3** is placed in the hose **70** connecting the blower **60** and the combustion generator burner section **22**.

In order to force air to recirculate, the pressure at the combination point **56** must be less than that at the takeoff point **36**. Since the stack **30** is typically designed to provide little frictional resistance to the exhausting flue gas, this implies that the blower **60** must operate to create a vacuum at the combination point **56**. Therefore, the air inlet line **50** must be sized small enough to provide some frictional resistance to airflow, even at low firing rates. This is what drives the exhaust gas through the recirculation line **40**. However, this pressure drop will be much less than required for a system employing a control valve on the air inlet line **50** or adjustable dampers, which results in an appreciable energy savings. Pressure drop balance refers to the fact that the amount of recirculation flue gas will be determined from the following equation:

Air Inlet pressure drop+Stack pressure drop=Flue Gas Recirculation line pressure drop

Each of these pressure drops is, essentially, proportional to velocity squared. Thus, as the firing rate changes, each of these three pressure drops will go up (or down) in the same proportion. Thus, the diameter and length of the air inlet line **50** can be sized relative to the length and diameter of recirculation line **40** to provide a selected percentage of flue gas recirculation without active control of the system **10**. The size and the shape of the air inlet line **50** can vary as long as the pressure drop ratio is sufficient to achieve the selected flue gas recirculation percentage.

By sizing the air inlet line **50** and the recirculation line **40**, a pressure drop is achieved which allows the flue gas to recirculate to reduce NO_x emissions. In order to fine tune the system **10**, a simple pressure drop device **80**, such as an orifice plate or a manually operated butterfly valve, can be installed. This pressure drop device **80** needs to be adjusted up to the point that the selected recirculation percentage is achieved. Upon reaching that point, further adjustment is not required.

The system **10** of the present invention reaches a steady-state operating condition where the pressures at the combination point **56** and the take off point **36** are maintained such that the condition of the system **10** does not change over time. Any change in pressure that does take place at either of the points will be continually balanced by a corresponding change in pressure at the other point. Particularly, air inlet line **50** is sized relative to recirculation line **40** such that the air inlet pressure drop (at combination point **56**) plus the stack pressure drop (at take off point **36**) equals the recirculation line **40** pressure drop. In this manner, the system **10** of the present invention passively maintains this steady-state condition of the selected percentage of flue gas recirculation. No active control of the system **10**, such as operation of valves or dampers, is required to maintain the operation of the system and, accordingly, the selected recirculation percentage.

As noted above, in order to monitor the flue gas recirculation percentage, temperature sensors **1, 2, 3** are installed in the system **10**. The first temperature sensor **1** is installed in the air inlet line **50**, above the combination point **56** as shown in FIG. **1**. This allows the temperature of the ambient air to be measured. The second temperature sensor **2** is installed in the recirculation line **40**. This allows the temperature of the flue gas to be measured at a point prior to reaching the combination point **56**. The third temperature sensor **3** is located downstream of the blower **60** in the hose **70** which connects the blower **60** with the burner section **22** of the combustion system **20**. The location of the third temperature sensor **3** downstream of the blower **60** causes some complexities in calculating the flue gas recirculation percentage due to the heat that the blower **60** adds to the mixed air and flue gas. Placing the third temperature sensor **3** upstream of the blower would have avoided this complexity, but the air would not be mixed well enough at this location to allow the precise measurements that are required for these calculations.

The typical equation that is used in calculating the flue gas recirculation percentage (FGR) is the following, where subscripts 1, 2, and 3 refer to locations of the temperature sensors one, two, and three as shown in the figures:

$$FGR = \frac{[Rate_2]}{[Rate_1 + Rate_2]} = \frac{[Rate_2]}{[Rate_3]}$$

From energy balance, assuming equal specific heat in each flow stream,

$$(Rate_1 * Temp_1) + (Rate_2 * Temp_2) = (Rate_3 * Temp_3)$$

Combining and simplifying gives,

$$FGR = \frac{[Temp_3 - Temp_1]}{[Temp_2 - Temp_1]}$$

An analogous equation, based on oxygen concentrations, can be used to monitor the process with oxygen sensors. However, these equations do not account for the heat added to the system due to mechanical inefficiencies of the blower **60**. In contrast to conventional systems, the present invention utilizes the following equation in order to account for such additional heat

$$FGR = \frac{[1.015 * T_3' - T_1]}{[1.087 * T_2 - 1.015 T_3']},$$

where T_3' is the difference between the temperature at the third temperature sensor **3** and the temperature change of the blower **60**.

The above equation is derived as follows:

From Conservation of Energy:

$$M_1 Cp_1 T_1 + M_2 Cp_2 T_2 = M_3 Cp_3 (T_3 - \Delta T_{Blower})$$

but:

$$M_3 = M_1 + M_2$$

and:

$$\Delta T_{Blower} = \frac{U_{Blower}}{M_3 Cp_3}.$$

Expanding the previous equation:

$$\Delta T_{Blower} = \frac{42.42(1 - \eta_{Blower}) HP_{Blower}}{(1 + FGR) Cp_3 Q_{gas} \gamma_{gas} \rho_{air} AFR}$$

But, knowing the affinity power relationships:

$$HP_1 = HP_2 \frac{T_2}{T_1} \left(\frac{N_1}{N_2} \right)^3$$

and calculating that:

$$Cp_3 \cong 1.015 Cp_1 = 0.2422 \frac{BTU}{lb_m - F^\circ}$$

$$Cp_2 \cong 1.087 Cp_1 = 0.2586 \frac{BTU}{lb_m - F^\circ}$$

and by assuming a 15% FGR, 1.5% O_2, 0.6 gas S.G., 60% η_{Blower} (thermal efficiency of blower), 19 AFR, and 0.076303 lb/ft^3 air density (STP=60° F.); and having measured a motor load of 83.51 HP at 2,070 RPM and 102° F., then:

$$\Delta T_{Blower} = \frac{4{,}887{,}074{,}500\left(\frac{N}{2{,}070}\right)^3}{(T_3+460)Q_{gas}}.$$

Let:

$$T_3' = T_3 - \Delta T_{Blower}$$

Then combining terms we find that the ratio of flue gas to air (FGR) is:

$$\frac{M_2}{M_1} = \frac{1.015T_3' - T_1}{1.087T_2 - 1.015T_3'}$$

Where M is the Mass flow rate,
HP is in horsepower,
N is in RPM,
T is in ° F.,
Cp is the specific heat in BTU/lbm-F°,
Q_{gas} (natural gas burned) is in Standard Cubic Feet per day,
FGR is the flue gas recirculation ratio, M_2/M_1, and
AFR is air to fuel ratio.

To more clearly describe the system, the following example is given. It is to be understood that the details and calculations shown below are simplified to describe the primary factors involved in calculating the flue gas recirculation percentage of a combustion system **20** as described. As would be apparent to one of ordinary skill in the art, other secondary factors may affect the flue gas recirculation percentage. This example should not represent any limitation on the present invention. Corresponding reference numerals will be used where appropriate.

The above-described system **10** has been implemented and tested. The system **10** shown in FIG. **3**, depicts a flue gas recirculation system **10** coupled to a combustion generator **20**. The system depicted in FIG. **3** is different from the embodiment in FIG. **1** in that the recirculation line is oriented differently and there is no flow restriction device depicted. It should be understood that the present invention does not require any particular orientation for recirculation line **40**, nor does it require a flow restriction device in the recirculation line. The system functions along the same principles and is included herein as one example of a specific configuration of the system of the present invention. In the embodiment shown in FIG. **3**, the flue gas recirculation system **10** includes an air inlet line **50** that is four feet long and eighteen inches in diameter. The stack **30** is sized large enough such that pressure losses are negligible. Since the diameter (i.e the ratio of the diameter of the air inlet line to the diameter of the recirculation line is about 1.8:1) of the exhaust stack **30** is sized so large, the pressure loss at the stack outlet **34** will not effect the pressure drop at the take off point **36** and the combination point **56**. The recirculation line **40** is sixty feet long and ten inches in diameter. Temperature data from an installation with this geometry was used to track the recirculation percentage of an operating generator, the results of which are shown in FIG. **4**. The flue gas recirculation percentage fluctuated between 16% and 22%. The standard deviation of this data is 2 percentage points.

NO_x emissions at the generator depicted in FIG. **3**, as measured with a separate analyzer, have been kept well below the allowable value of 30 ppm. Tests on other generators demonstrate that the recirculation percentage can be as low as 10%, and still achieve the desired NO_x control of less than 30 ppm. FIG. **5** depicts a graph of steam generator performance using the system of the present invention. Particularly, a graph of oxides of nitrogen (ppm) as a function of Flue Gas Recirculation rate (% FGR) is shown. As is apparent, the system of the present invention consistently achieves NO_x values well below 30 ppm over a considerable range of % FGR (13–18%). As demonstrated by FIG. **5**. the system of the present invention can achieve NO_x values below 10 ppm. The system used to obtain the data shown in both FIGS. **4** and **5** did not contain a pressure drop device **80** in recirculation line **40**, thereby demonstrating the effectiveness of the system of the present invention, and the efficacy of the steady-state configuration.

As described above, and as shown in the above example, the present invention provides a simple system for flue gas recirculation. It should be apparent that the present invention may be used to increase efficiency, to lower equipment costs and operating costs, and to simplify the calculation of flue gas recirculation percentage while achieving more accurate results.

Conclusion

While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of the present invention should not be limited by ally of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

We claim:

1. A method for determining flue gas recirculation percentage comprising:

measuring a first temperature (T_1) at a first temperature sensor in an air inlet line for providing air to a combustion generator;

measuring a second temperature (T_2) at a second temperature sensor in a recirculation line coupled between the air inlet line and an exhaust stack of the combustion generator;

measuring a third temperature (T_3) at a third temperature sensor in a line coupled between a blower and a burner section of the combustion generator;

calculating a temperature factor (T_3') by subtracting the temperature of said blower from T_3; and

calculating the flue gas recirculation (FGR) percentage in accordance with the following equation

$$FGR = \frac{(1.015 * T_3' - T_1)}{(1.087 * T_2 - 1.015 * T_3')}.$$

2. The method of claim **1**, wherein T_1 is measured at the first temperature sensor which is disposed upstream of the point where the air inlet line is coupled to the recirculation line and T_3 is measured at the third temperature sensor which is disposed downstream of the blower.

3. The method of claim **2**, wherein T_1 is measured upstream of T_3.

4. The method of claim **1**, further comprising the step of passively maintaining the calculated FGR percentage to achieve a corresponding reduction in NO_x emission.

5. The method of claim **4**, wherein said step of passively maintaining the calculated FGR percentage comprises sizing the air inlet line relative to the recirculation line such that an air inlet pressure drop plus an exhaust stack pressure drop equals a recirculation line pressure drop.

6. The method of claim **4**, wherein said step of passively maintaining the calculated FGR percentage comprises sizing the recirculation line such that the pressure where the recirculation line couples the air inlet line is less than the pressure where the recirculation line couples the exhaust stack.

7. The method of claim **4**, wherein said step of passively maintaining the calculated FGR percentage comprises sizing the air inlet line such that the pressure where the recirculation line couples the air inlet line is less than the pressure where the recirculation line couples the exhaust stack.

8. The method of claim **4**, further comprising: providing a flow restriction device in the recirculation line.

9. The method of claim **8**, wherein the flow restriction device is an orifice plate.

10. The method of claim **8**, wherein the flow restriction device is a valve.

* * * * *